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Mars Dynamics from Earth-Based Tracking of the Mars Pathfinder Lander

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Abstract

Measurements of Mars' rotational variations can be conducted via Earth-based radio tracking observations of the Mars Pathfinder lander during an extended mission. Two-way range measurements between an Earth antenna and the lander will enable precise monitoring of the planet's orientation and length-of-day variations, allowing details of Mars' internal structure and global surface/ atmosphere interactions to be determined with precision for the first time. An analysis has been performed to investigate the accuracy with which key physical parameters of Mars can be determined using the Earth-based radio tracking measurements. Acquisition of such measurements over one Martian year should enable determination of Mars' polar moment of inertia to 1% or better, providing a strong constraint on radial density profiles (and hence on the iron content of the core and mantle) and on long-term variations of the obliquity and climate of Mars. Variations in Mars length of day and polar motion should also be detectable, and will yield information on the seasonal cycling of CO_2 between the atmosphere and the surface.

Introduction

Mars Pathfinder will have an X-band (8 GHz) radio system for direct-to-Earth communications and for range and Doppler measurements. A program of precise range and Doppler observations will provide determinations of" the changing orbits of Earth and Mars and of the rotation of Mars which will complement the Viking lander range observations obtained in 1977-1982 [*Standish et al.*, 1995; *Yoder and Standish*, 19Wtllis issue]. of particular interest is the Martian rotational information: secular precession of the longitude of the node, short period nutation of the obliquity and node, seasonal and tidal variations in the diurnal, axial rotation (i.e. UT0) of Mars and Chandler-like wobble of Mars figure axis relative to the spin axis. These seasonal variations in UT0 and polar motion are primarily driven by the waxing and waning CO_2 caps whose changes can be monitored by the surface air pressure variations [*Cazenave and Balmino*, 1980; *Chao and Rubincam*, 1992]. SLY-sonal variations of UT0 have already been detected [*Reasenberg et al.*, 1979a; *Yoder and Standish*, 1996], although their precision is not yet great enough to provide a useful constraint for climate studies. We believe Pathfinder-determined UT0 will provide this important new data set if the lander lasts more than one-half 01" a Martian year.

Of even greater geophysical significance is the expectation that a few months of Pathfinder ranging data will determine the mean spatial orientation of the pole of' rotation of Mars to within ().5". The 6 years of Mars ranging obtained by Viking landers also constrains the mean pole at the midpoint of that experiment to about 0.5". The pole precession of about $7.78''/yr$ was determined to 5% by the Viking lander data [*Yoder and Standish*, 1996]. The precession is driven by the gravitational torque of the sun acting on Mars oblateness and is proportional to $(C(1 \; /2(,4 \; -B))/C$ where $C > B > A$ are principal moments of inertia. Tracking data of the Pathfinder lander, when combined with the Viking lander data acquired 24 years earlier, should resolve the precession rate to better than 1 % if the mission lasts over one-half of a Martian year. Since the factor $C \cdot \frac{1}{2}(A\text{-}IB) = J_2MR^2$ is already known to high accuracy [*Smith et al.*, 1993; *Konopliv and Sjogren*, 1995] fi 0111 detection of Mars gravity field using Viking orbiter and other tracking data, this improved estimate of" the mean precession will constrain the polar moment of inertia C.

Accurate measurement of the polar moment of inertia will provide significant information about the composition and internal structure of Mars [*Bills*, 1990; *Yoder and Standish*, 19{16]. Figure 3 in *Yoder and Standish* illustrates the sensitivity of moment to both mantle composition, mantle temperature and core size. The important point to note is that constraining the core moment will drastically limit the range of plausible interior structural models. The Viking estimate for the precession constrains the pole moment to 0.357±0.16. This provocative estimate lies between the upper bound 0.365 deduced by *Reasenberg* [1977] and *Kaula et al.* [1989] from the effect of the Tharsis bulge and the value of 0.345 derived by *Bills* [1989] based on a statistical argument.

The polar moment of inertia is also a key parameter for understanding the past climate of Mars 011 a time scale of a few million years. The gravitational pull by Jupiter and the other planets slowly change the orbital plane of Mars and, over millions of years, causes the obliquity to change tens Of degrees. This change alters the mean solar insolation at the poles by a factor of two. The exact history of Mars obliquity is very sensitive to the polar moment of inertia [*Ward*, 1973; 1974; *Toon et al.*, 1980; *Laskar*, 1988; *Ward and Rudy*, 1991; *Touma and Wisdom*, 1993]. Even a 1 % difference in the polar moment of inertia can lead to a ten degree difference in knowledge of the obliquity as indicated in Fig. 1 fl'oil) *Ward and Rudy* [1991]. Large uncertainties in the obliquity history lead to large uncertainties in insolation and thus in past global climate. Hence, accurate determination of the precession constant will improve knowledge of the Martian climate over the last few million years.

Data collected by the Viking landers show a seasonal variation in atmospheric pressure of 20% [*Ryan et al.*, 1978; *Hess et al.*, 1980, *Tillman et al.*, 1993]. This variation is thought to be due to condensation of carbon dioxide at the poles in winter and evaporation in summer. The change in the amount of condensed carbon dioxide results in a change in the moment of inertia. *Cazenave and Balmino* [1981] predict seasonal changes in the rotation rate in response to the moment of inertia change, with an amplitude corresponding to a change in rotation" of about 300 mas (milliarcsecond), corresponding to a displacement of 5 m at the equator. However, the use of pressure measurements from only two sites on the planet could lead to significant errors in the prediction of the global exchange of carbon dioxide, perhaps as large as 50%. This annual signature is observed in the Viking data although no attempt has been made to remove a possible polar motion contribution. our preliminary analysis indicates that the more accurate Pathfinder radio system will enable the measurement of the rotation variation with an accuracy of about < 40 *mas* provided that the mission survives more than one-half of a Martian year. These data, when combined with local pressure observations by the lander, will allow a better model for the global CO_2 cycle.

In addition to the above investigations of Mars' rotational variations with their implications for better understanding of the past Mars climate, carbon dioxide cycle, and mantle composition, radio tracking of the lander provides the opportunity to monitor the orbital dynamics of Mars. Ranging measurements to the Viking landers have been used to accurately determine the ephemerides of Earth and Mars [e. g. *Standish and Williams,* 1990], determine the masses of three large asteroids through their influence on the orbit of Mars [*Standish and Hellings,* 1988], estimate the PPN (Parameterized Post-Newtonian) parameter gamma [*Reasenberg et al.,* 1979b; *Reasenberg et al.,* 1981; *Hellings et al.,* 1983; *Shapiro,* 1990] and set a limit on a possible rate of change of the gravitational constant G [*Hellings et al.,* 1983]. Pathfinder ranging measurements will significantly improve estimates of these parameters.

Experiment description

The range ρ from a lander on Mars to the Earth is related to the orbit and orientation of Mars by

$$\rho \approx d + R_z \sin\delta_d + R_\perp \cos\delta_d \cos H_d \qquad (1)$$

where d is the distance from the center of Mars to the center of Earth, $R_\perp$ is the lander distance from the instantaneous rotation axis, R_z is the displacement of the lander from the equatorial plane, δ_d is the declination of Earth as seen from Mars, and H_d is the hour angle of Earth. The declination and hour angle of Earth are given by

$$\begin{aligned} \sin\delta_d &\approx \sin\epsilon \sin(L_d - \psi) \\ H_d &\approx \phi + \psi - \lambda_0 - L_d \\ L_d &= L + \arcsin(r_\oplus sinS/d) \qquad (2) \\ d &= (r^2 + r_\oplus{}^2 - 2rr_\oplus \cos S)^{\frac{1}{2}} \\ cosS &= \hat{\mathbf{r}} \cdot \hat{\mathbf{r}}_\oplus \end{aligned}$$

where ϵ is the obliquity of Mars, ψ is the longitude of the node of Mars, L is the ecliptic longitude of Mars, ϕ is the rotation angle of Mars about its spin axis, λ_0 is the lander longitude, r is the heliocentric distance of Mars, $r_\oplus$ is the heliocentric distance of the Earth, and S is the angle between the sun-Mars direction and the sun-Earth direction (The motion of the Earth tracking station due to Earth rotation is ignored; this is very accurately determined using other data.)

Sensitivity to the direction of the Martian spin axis, and the precession and nutation which change this direction, comes mainly through changes in the $\cos\delta_d$ term modulating the amplitude of the hour-angle factor of Eqn. 1. Polar motion causes changes in the lander coordinates with respect to the spin axis, changing the latitude and longitude of the station. With only one lander it is not possible to separate changes in longitude due to polar motion from changes in the rotation rate. The determined quantities are variation in latitude, mainly evident through changes in the spin radius which modulates the hour-angle term of Eqn. 1, and UT0, changes in instantaneous lander longitude which appear as changes in the hour-angle.

The Viking landers provided a series of range measurements from July 1976 to November 1982. Most of these measurements are from Viking lander 1, since Viking lander 2 stopped transmitting after September 1977, and most of the tracking passes were limited to a few range measurements. The Viking ranging measurements were performed using a signal transmitted from a tracking station transponded by the lander and the round trip time measured. Early analysis of part of Viking data set was done to determine the direction of the spin axis and the rotation rate of Mars but the precession rate was not measurable at a significant level [*Michael et al.,* 1976; *Mayo et* al., 1977; *Borderies et al.,* 1980]. Recently *Yoder and Standish* [1996] have analyzed the full Viking lander data set and determined the precession rate with uncertainty of about 5%.

Range and Doppler measurements to the Mars Pathfinder lander can contribute to estimates of the rotational state of Mars. Within a single tracking pass both range and Doppler data can measure a sinusoidal signature due to the diurnal rotation of Mars. The Doppler data are typically able to measure this signature more accurately than the range measurements, depending on various parameters of the radio system. The ranging data provide the ability to connect information from separate tracking passes. The accuracy of the Pathfinder measurements are expected to be although no attempt has been made to remove a possible polar motion contribution. Our preliminary analysis indicates that the more accurate Pathfinder radio system will enable the measurement of the rotation variation with an accuracy of about < 40 *mas* provided that the mission survives more than one-half of a Martian year. These data, when combined with local pressure observations by the lander, will allow a better model for the global CO_2 cycle.

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$\vec{r}$ is given by

$$\vec{r} = I_z \; N) R_x(-J) R_z(-\psi) R_x(-\;) \\ \times \; R_z(-\phi) R_y(X_p) R_x(Y_p) \vec{x} \tag{3}$$

where X_p and Y_p describe the crust-fixed coordinates of Mars' spin axis; ϕ is the rotation about the spin axis; I is the inclination of the (instantaneous) Mars equator to the (fixed) Mars mean orbit plane of J2000; ψ is the longitude of the Mars spin axis in the mean Mars orbital plane of J2000 measured with respect to the intersection of Mars mean orbit and Earth-s mean equator of J2000; N and J transform between the inertial Mars- mean-orbit system and the Earth-mean-equator system of J2000 with J the inclination of Mars mean orbital plane and Earth's mean equator and N is the angle between Earth's equinox and the intersection of Mars' mean orbit and Earth-s mean equator of J2000.

For a rigid Mars, the changes in the direction of Mars' spin axis in inertial space due to torques from the Sun and other solar system bodies are described by series expansions of the angles I and ψ;

$$I(t) = I_0 + \sum I_m \cos(\alpha_m t \quad \theta_m)$$

$$\psi(t) = \psi_0 \; \dot{\psi} t \quad \sum \psi_m \sin(\alpha_m t + \theta_m) \tag{4}$$

The trigonometric arguments in Eqn. 4 involves multiples of the mean anomaly M and the angle $q = 2\Omega + 2\omega - 2\psi$ where Ω is the longitude of Mars ascending node with respect to the Earth mean ecliptic and ω is the argument of periapsis. The rate of change of M is the mean motion n while the rate of change of q is negligible. The amplitude coefficients I_m, $\dot{\psi}$, and ψ_m are functions of Mars' orbital elements and principle moments of inertia. Only a small number of terms is needed to describe the motion of Mars' pole at the milliarcsecond level.

To model Mars as a fluid core and a rigid mantle, the periodic motion of the spin axis is expressed in prograde and retrograde terms;

$$I_m \cos(\alpha_m t + \theta_m) + i \sin(I_0) \psi_m \sin(\alpha_m t + \theta_m) \\ = r_m \exp - (\alpha_m t + \theta_m) + \exp \alpha_m t + \theta_m \tag{5}$$

The nominal prograde and retrograde coefficients p_m and r_m are modified by the fluid core according to [*Sasao et al.*, 1980]

$$r'_m = r_m [1 + F \frac{}{- \alpha_m - \sigma_0}] \\ p'_m = p_m [1 \quad F \frac{\alpha_m}{\alpha_m - \sigma_0}] \\ F = \frac{C_f}{C - C_f} \quad \frac{\gamma}{c_f} \tag{6}$$

where C_f is the polar moment of inertia of the fluid core only, σ_0 is the free angular rotation rate of the fluid core, γ is the dynamic elasticity of the core-mantle boundary, and c_f is an elastic correction for the core-mantle boundary.

Estimation strategy

The Viking lander and simulated Mars Pathfinder range were combined to determine Mars orbit and rotation parameters. The complete list of estimated parameters is given in Table 1. The direction of the pole at a reference epoch, I_0 and ψ_0 , were estimated along with the polar moment of inertia C, the core moment factor F, and the free core rotation rate σ_0. The core moment of inertia was initially constrained to be known to within 7% of the nominal total moment of inertia based on the range of reasonable core compositions. The other parameters were loosely constrained.

The rotation about the pole (UT1) was modeled as an initial value, a rotation rate, and annual, biannual, and triannual in-phase and out-of-phase (sine and cosine) variations in UT1. Mars polar motion was modeled similarly. In addition a small random- walk variation in polar motion and UT1 was estimated with a weekly increase in uncertainty of about 2.5 *mas*. This weekly variation is about the level of variation for UT1 seen on the Earth; assuming the same rotational variability for Mars is probably conservative.

The initial polar motion angle and rotation angle about the pole were fixed to nominal values; this defined the Mars-fixed coordinate frame. The locations of each lander were estimated with respect to this frame. The amplitudes of the periodic variations in polar motion and rotation about the pole were assigned independent a priori uncertainties of $1''$ corresponding to a displacement of 20 m at the equator. Data from one lander determine only variation in latitude and UT0. Because there is very little data from Viking lander 2, the Viking lander range data determine well only the variation in latitude and UT0 for Viking lander 1. Mars Pathfinder will have sensitivity to the component of polar motion not detected in the Viking lander 1 range data. Therefore the periodic variation in latitude and UT0 amplitudes were estimated independently for the two data sets. If the polar motion turns out to be small then it will be possible to get improved estimates of the (long-term) periodic rotation rate variations by treating the UT0 for the two missions as correlated.

Treating the Earth rotation and tracking station locations as known defines the inertial coordinate system. In addition to the Mars rotation parameters, orbital elements for Earth and Mars were estimated with large a priori uncertainties expect for a constraint on the orientation of the Earth's orbit, which is known with respect to the inertial extragalactic radio source frame with an accuracy of 10 *mas* through comparison of Earth orientation measurement made by lunar laser ranging and very-long baseline interferometry [*Folkner et al.*, 1993]. Orbit perturbations due to asteroids were not included in this study; their inclusion would tend to slightly degrade the expected accuracies but this would be partly offset by including more data that determine the Earth and Mars orbits, such as lunar laser ranging and ranging to Mars orbiters.

Covariance results

The Viking data were combined with a varying amount of simulated data from Pathfinder to investigate how the estimates of Mars rotation parameters improved with the duration of the Pathfinder mission. The parameters of most interest are the polar moment of inertia and the periodic rotation amplitudes. Figure 1 shows the expected formal uncertainty of the moment of inertia as a function of mission lifetime. The uncertainty in moment of inertia at the start of the Pathfinder mission is the formal uncertainty (from this study) as a result of only the Viking lander data. The estimated uncertainty of the in-phase annual, biannual, and triannual UT0 variations are shown as a function of mission lifetime in Fig. 2. The uncertainties in the out-of-phase components are comparable. The UT0 amplitude uncertainties at the start of the Pathfinder mission are the assumed a priori levels since no correlation with the Viking rotation variations are assumed. Figure 3 shows the uncertainty in the periodic variation in latitude.

The results shown in these figures are formal uncertainties and are optimistic because some noise sources, such as asteroid perturbations and media variations, have been ignored. However, the most significant parameters have been included. Also it may be possible to improve the formal accuracy by optimization of the data schedule and by including lander Doppler data and data from the Mars Global Surveyor orbiter. Furthermore it is probably pessimistic to assume the Mars has random rotation variations as large as those on Earth, as was assumed in this analysis. The addition of Doppler data, and the effect of the random rotation variations, were investigated for a Pathfinder mission lifetime of one Martian year. Table 2 gives the estimated rotation parameter uncertainty using either Doppler only, range only, or both range and Doppler, with or without an assumed random rotation rate variation. The Doppler data were assumed to have a white frequency noise of 0.1 mm/s for 60 s sample time, which is characteristic of the DSN X-band system performance. (The Doppler data are more sensitive to Earth media effects, which have been ignored.) It can be seen that the Doppler data alone are comparable to the range in the ability to estimate the Mars rotation parameters if Mars rotation varies as randomly as the Earth. If Mars is assumed to have no (or negligible) random rotation variation then the Doppler data has some additional strength to estimate the free core rotation rate and has some sensitivity to the fluid core moment of inertia, as evidenced by a slight reduction in the uncertainty of F from the 0.07 a priori uncertainty.

Conclusion

With an extended mission, tracking measurement of Mars Pathfinder, when combined with the Viking lander data set, should be able to determine the polar moment of inertia to better than 1% and to confidently detect seasonal rotation variations with an accuracy of about 15% yielding information about the seasonal mass redistribution on a global scale. This accuracy would be significantly improved if the duration of each transmission period could be lengthened, either by devoting more energy to each transmission or cycling the transponder on and off. A campaign involving simultaneous ranging to the Mars Global Surveyor spacecraft, which reaches Mars soon after Pathfinder, might lead to further improvements. Such a program may also detect the presence of a fluid core, either through the effect it has on the short period nutations, the tidal contribution to UT0 [*Yoder and Standish*, 1996], or on the tidal perturbation of the Mars Global Surveyor spacecraft [*Konopliv and Yoder*, 1996].

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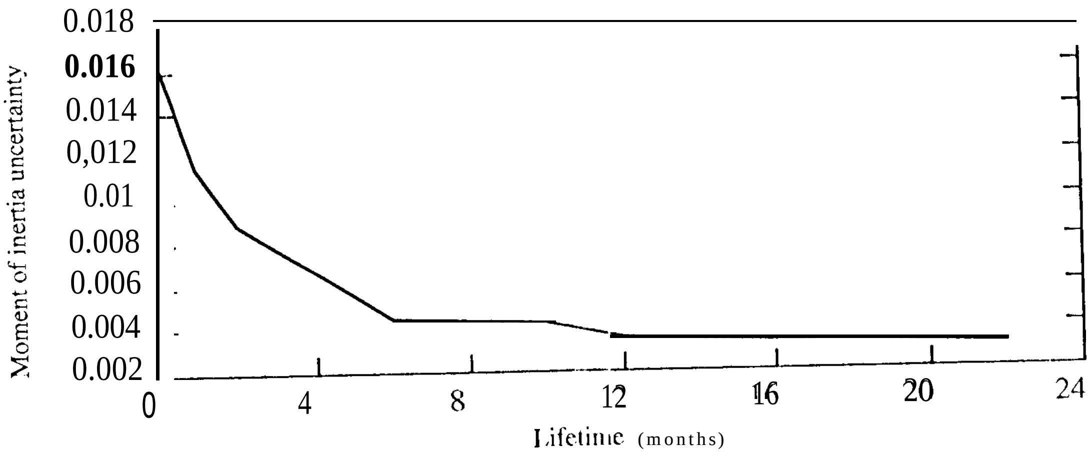

Figure 1 Expected accuracy of polar moment o f inertia versus Pathfinder lander lifetime.

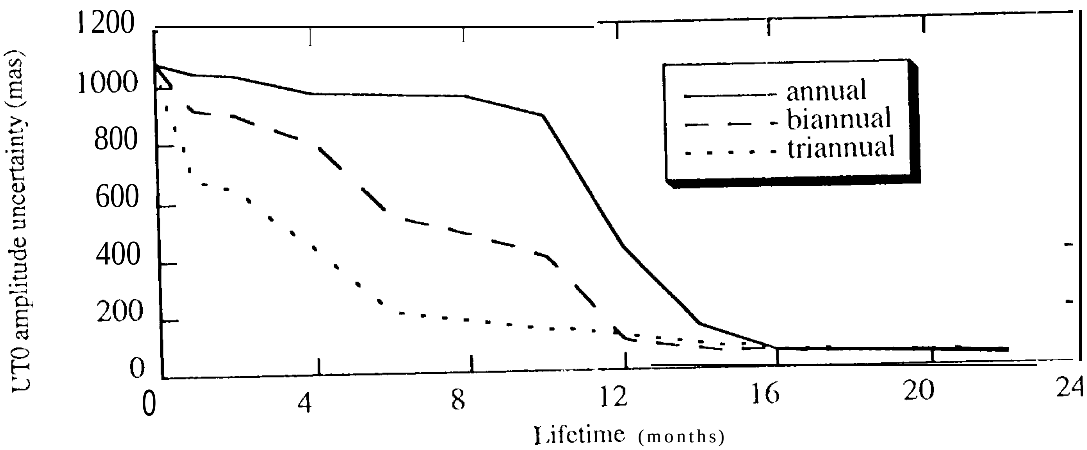

Figure 2. Accuracy of UT0 variations versus Pathfinder lander lifetime.

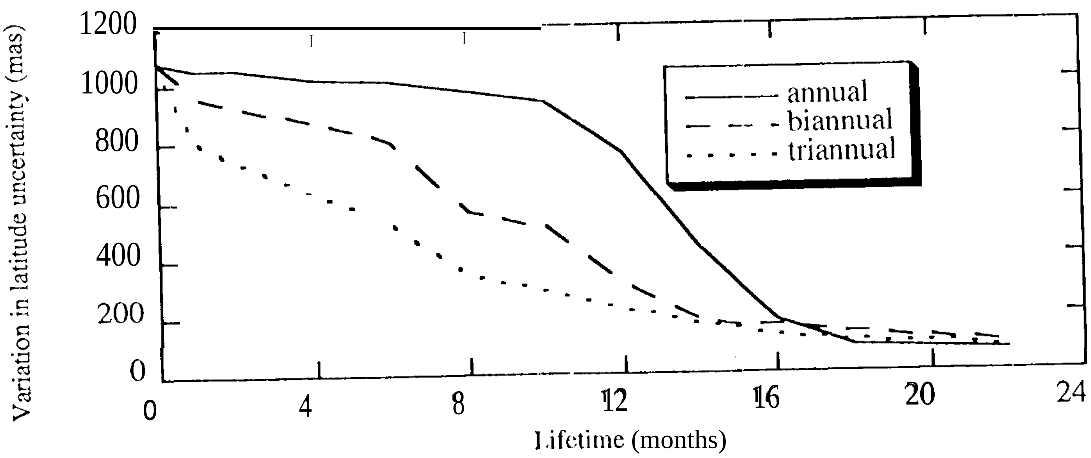

Figure 3. Accuracy of variation in latitude versus Pathfinder lander lifetime.

'1'able 1. Estimated parameters and uncertainties

Parameter	a priori uncertainty
Total moment of inertia, C/MR^2	**0.5**
Core moment factor, F	0.07
Free core nutation rate σ_0	$1.5°/day$
Obliquity at J2000 I_0	**0.5**
Pole longitude at J2000, ψ_0	*0.5*
Rotation rate	$1°/day$
UT1 annual in- phase amplitude	$1''$
UT1 annual out-of-phase amplitude	1 "
UT1 biannual in-phase amplitude	$1''$
UT1 biannual out-of-phase amplitude	' "
UT1 triannual in-phase amplitude	$1''$
UT1 triannual out-of-phase amplitude	$1''$
Polar motion annual in-phase amplitude	$1''$
Polar motion annual out-of-phase amplitude	$1''$
Polar motion biannual in-phase amplitude	$1''$
Polar motion biannual out-of-p hase amplitude	$1''$
Polar motion triannual in-phase amplitude	$1''$
Polar motion triannual out-of-p hase amplitude	$1''$
Lander locations	$1000km$ (each component)
Earth orbit orientation	$10mas$ (each component)
Earth semimajor axis	$0.1AU$
Earth eccentricity	0.1
Earth longitude of perhelion	$1''$
Mars orbit orientation	1 " (each component)
Mars semimajor axis	$0.1AU$
Mars eccentricity	*0.1*
Mars longitude of perhelion	$1''$

Table 2. Mars rotation parameter uncertainties for different data and modeling assumptions

Parameter	Earth-like random rotation			No random rotation		
	Range	Doppler	Both	Range	Doppler	Both
Total moment of inertia, C/MR^2	0.00312	0.00328	0.00281	0.00306	0.00223	0.00199
Core moment factor, F	0.0689	0.0665	0.0659	0.0688	0.0515	0.0505
Free core nutation rate $\sigma_0 (deg/day)$	0.663	0.230	0.226	0.634	0.128	0.125
UT1 annual in-phase (mas)	38	28	27	27	8	8
UT1 biannual in-phase (mas)	48	37	37	45	26	25
UT1 triannual in-phase (mas)	50	21	20	46	[illegible]	7
Polar motion annual in-phase (mas)	76	37	36	61	7	7
Polar motion biannual in-phase (mas)	101	47	42	96	17	16
Polar motion triannual in-phase (mas)	80	41	37	74	17	16